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Variability of Antarctic sea ice 1979–1998

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[1] The principal characteristics of the variability of Antarctic sea ice cover as previously described from satellite passive microwave observations are also evident in a systematically calibrated and analyzed data set for 20.2 years (1979–1998). The total Antarctic sea ice extent (concentration >15%) increased by 11,180 ± 4190 km^2 yr^{-1} (0.98 ± 0.37% (decade)$^{-1}$). The increase in the area of sea ice within the extent boundary is similar (10,860 ± 3720 km^2 yr^{-1} and 1.26 ± 0.43% (decade)$^{-1}$). Regionally, the trends in extent are positive in the Weddel Sea (1.4 ± 0.9% (decade)$^{-1}$), Pacific Ocean (2.0 ± 1.4% (decade)$^{-1}$), and Ross (6.7 ± 1.1% (decade)$^{-1}$) sectors, slightly negative in the Indian Ocean (−1.0 ± 1.0% (decade)$^{-1}$), and strongly negative in the Bellingshausen-Amundsen Seas sector (−9.7 ± 1.5% (decade)$^{-1}$). For the entire ice pack, ice increases occur in all seasons, with the largest increase during fall. On a regional basis the trends differ season to season. During summer and fall the trends are positive or near zero in all sectors except the Bellingshausen-Amundsen Seas sector. During winter and spring the trends are negative or near zero in all sectors except the Ross Sea, which has positive trends in all seasons. Components of interannual variability with periods of about 3–5 years are regionally large but tend to counterbalance each other in the total ice pack. The interannual variability of the annual mean sea ice extent is only 1.6% overall, compared to 6–9% in each of five regional sectors. Analysis of the relation between regional sea ice extents and spatially averaged surface temperatures over the ice pack gives an overall sensitivity between winter ice cover and temperature of −0.7% change in sea ice extent per degree Kelvin. For summer some regional ice extents vary positively with temperature, and others vary negatively. The observed increase in Antarctic sea ice cover is counter to the observed decreases in the Arctic. It is also qualitatively consistent with the counterintuitive prediction of a global atmospheric-ocean model of increasing sea ice around Antarctica with climate warming due to the stabilizing effects of increased snowfall on the Southern Ocean. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 1635 Global Change: Oceans (4203); 1640 Global Change: Remote sensing; 4207 Oceanography: General: Arctic and Antarctic oceanography; *KEYWORDS:* sea ice, Antarctic, climate, passive microwave, Southern Ocean

1. Introduction

[2] In recent decades the Antarctic sea ice cover has varied significantly from year to year with some anomalies persisting for periods of 3–5 years [e.g., *Zwally et al.*, 1983a]. However, decadal-scale sea ice changes have been smaller and more difficult to ascertain with statistical significance. Furthermore, while the physical processes (ice-ocean-atmosphere-solar) that control the annual growth and decay of sea ice are well known, the manner in which these processes combine on decadal timescales and regional spatial scales is complex and not well determined. In particular, the interaction of the Antarctic sea ice cover with global climate change is uncertain. In one view the intuitive expectation that a smaller sea ice cover should be associated with warmer atmospheric temperatures is supported by some observations and models. For example, *Gordon and O'Farrell* [1997] modeled a decreasing Antarctic sea ice cover in a warmer climate but with a smaller rate of decrease than their modeled rate of decrease for the Arctic sea ice. Observationally, *Jacka and Budd* [1991] and *Weatherly et al.* [1991] also showed the expected negative correlation between regional-scale sea ice changes and Antarctic coastal air temperatures. In another view, at least one climate model, which included coupled ice-ocean-atmosphere interactions [*Manabe et al.*, 1992], gives the counter-intuitive result that the sea ice cover would actually increase with global climate warming. The physical processes in the model that cause the predicted sea ice increase are increased precipitation with a warmer atmosphere in polar regions, more snowfall on sea ice, lower salinity in the near-surface ocean layers, more stable mixed layer and reduced heat flux to the surface, and consequently, more sea ice.

[3] Clearly, if changes in the distribution of Antarctic sea ice are expected to be indicative of global climate change, a better understanding of the nature and causes of Antarctic sea ice variability is required. In particular, we should know whether Antarctic sea ice is expected to increase or decrease with climate warming. In this paper we describe the variability of the Antarctic ice cover in detail, including the variations in regional sectors as defined by *Zwally et al.* [1983b] and *Gloersen et al.* [1992], using 20 years of well-calibrated data. We believe the characteristics of the observed sea ice variability of the Antarctic provide new insights to the interplay of the relevant physical and climatic processes on seasonal to decadal timescales. In particular, our analysis of the decadal-scale trends in sea ice by season show that the trend of increasing Antarctic sea ice cover is dominated by summer and autumn increases and that changes in the winter are near zero overall. These results are important because the dominant climatic processes controlling the distribution of sea ice around the time of the winter maximum extent are likely to be

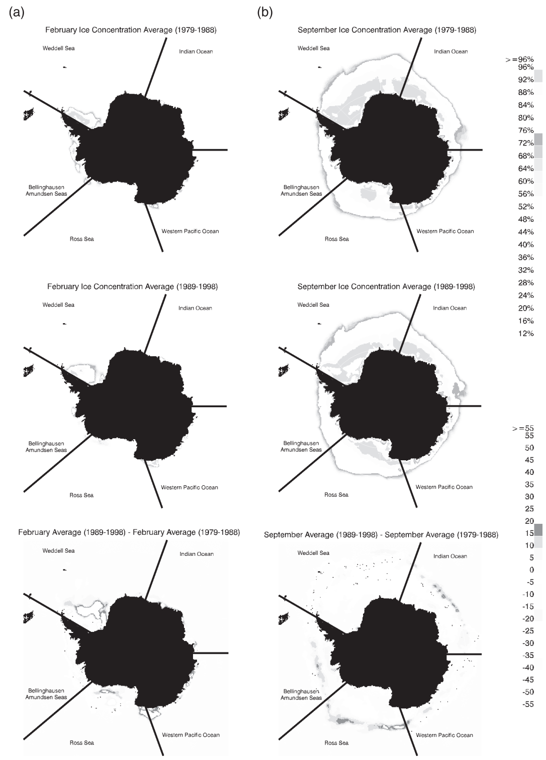

Figure 1. Average sea ice concentration maps averaged over (top) the first 10 years (1979–1988) and (middle) the second 10 years (1989–1998) and (bottom) their differences for (a) February, the month of summer minimum and (b) September, the month of winter maximum. The five regional sectors are Weddell Sea (60°W–20°E), Indian Ocean (20°–90°E), Pacific Ocean (90°–160°E), Ross Sea (160°–140°W), and Bellingshausen-Amundsen Seas (140°–60°W). See color version of this figure at back of this issue.

significantly different than those near the summer minimum. Examination of potential correlations between temperature (using new satellite estimates of surface temperature averaged over the sea ice pack) and sea ice extent shows a wintertime correlation on a regional basis, which gives an estimate of the sensitivity of sea ice cover to temperature change.

2. Background

[4] Since the advent of satellite remote sensing, the study of interannual changes in the Antarctic sea ice cover and their possible climatic significance have been the subject of numerous investigations. Initially, the use of relatively short or poorly calibrated satellite historical records caused some conflicting results regarding trends in ice extent [e.g., *Kukla*, 1978; *Kukla and Gavin*, 1981; *Zwally et al.*, 1983a]. Even with the sole use of longer and more consistent passive microwave data, the trends from analysis of the same set of satellite data have differed [*Johannessen et al.*, 1995; *Bjørgo et al.*, 1997; *Cavalieri et al.*, 1997; *Stammerjohn and Smith*, 1997]. This is partly because the satellite sensors have finite lifetimes and the time series is made up of measurements from different sensors, some of which have different footprints and characteristics than the others. Furthermore, different investigators use different ice algorithms for the retrieval of ice parameters and their own techniques for removing abnormal values in the land/ocean boundaries and the open ocean. During periods of overlap the different sensors also provide slightly different sea ice extents and actual areas, even with the same techniques. Therefore further intersensor adjustments are required to match the overlap results and obtain a uniform time series.

[5] For the period of November 1978 through December 1996, *Cavalieri et al.* [1997] found an asymmetry in the trends of decreasing Arctic sea ice extent ($-2.9 \pm 0.4\%$ (decade)$^{-1}$) and increasing Antarctic sea ice extent ($+1.3 \pm 0.2\%$ (decade)$^{-1}$). *Cavalieri et al.* [1997] also reviewed the results of previous analyses, which used essentially the same multisatellite passive microwave data set but with some different methodologies and conclusions about the apparent trends in the Antarctic sea ice. The methodologies for sea ice mapping and intersatellite calibration techniques employed by *Cavalieri et al.* [1997] to produce a data [e.g., see *Steffen et al.*, 1992].

9. Discussion and Conclusions

[51] A primary result of this analysis of the 20 years of measurements of sea ice concentration on the Southern Ocean is the $+11{,}181 \pm 4190$ km^2 yr^{-1} ($+0.98 \pm 0.37\%$ (decade)$^{-1}$) increase in sea ice extent and a very similar $+10{,}860 \pm 3720$ km^2 yr^{-1} ($+1.26 \pm 0.43\%$ (decade)$^{-1}$) increase in sea ice area. Regionally, the trends in extent are positive in the Weddell Sea ($1.4 \pm 0.9\%$ (decade)$^{-1}$), Pacific Ocean ($2.0 \pm 1.4\%$ (decade)$^{-1}$), and Ross Sea ($6.7 \pm 1.1\%$ (decade)$^{-1}$) sectors, slightly negative in the Indian Ocean ($-1.0 \pm 1.0\%$ (decade)$^{-1}$), and negative in the Bellingshausen/Amundsen Seas sector ($-9.7 \pm 1.5\%$ (decade)$^{-1}$). An overall increase in Antarctic sea ice cover, during a period when global climate appears to have been warming by 0.2 K (decade)$^{-1}$ [*Hansen et al.*, 1999], stands in marked contrast to the observed decrease in the Arctic sea ice extent of $-34{,}300 \pm 3700$ km^2 yr^{-1} ($-2.8 \pm 0.3\%$ (decade)$^{-1}$) and sea ice area of $-29{,}500 \pm 3800$ km^2 yr^{-1} ($-2.8 \pm 0.4\%$ (decade)$^{-1}$) in sea ice area [*Parkinson et al.*, 1999]. The observed decrease in the Arctic has been partially attributed to greenhouse warming through climate model simulations with increased CO_2 and aerosols [*Vinnikov et al.*, 1999]. As discussed in section 1, an increasing Antarctic sea ice cover is consistent with at least one climate model that includes coupled ice-ocean-atmosphere interactions and a doubling of CO_2 content over 80 years [*Manabe et al.*, 1992].

[52] Another main aspect of the results is the seasonality of the changes, being largest in autumn in both magnitude ($+24{,}700 \pm 17{,}500$ km^2 yr^{-1}) and percentage ($+2.5 \pm 1.8\%$ (decade)$^{-1}$) and second largest in summer ($+6700 \pm 12{,}600$ km^2 yr^{-1} and $+1.7 \pm 3.2\%$ (decade)$^{-1}$) in terms of percentage change. The changes for the winter season ($+7400 \pm 8500$ km^2 yr^{-1} and $+0.4 \pm 0.5\%$ (decade)$^{-1}$) and for spring ($+10{,}100 \pm 14{,}000$ km^2 yr^{-1} and $+0.7 \pm 1.0\%$ (decade)$^{-1}$) are small as a fractional change. On a regional basis the trends differ season to season. During summer and fall the trends are positive or near zero in all sectors except the Bellingshausen/Amundsen Seas sector. During winter and spring the trends are negative or near zero in all sectors except the Ross Sea, which has positive trends in all seasons.

[53] In the context of climate change the sensitivity of the sea ice to changes in temperature is of particular interest. Analysis of the relation between regional sea ice extents and spatially averaged surface temperatures over the ice pack gives an overall sensitivity between winter ice cover and temperature of -0.70% change in sea ice extent per degree Kelvin ($-0.11 \pm 0.09 \times 10^6$ km^2 K^{-1}). A change in the winter ice extent of 0.70% corresponds to a latitudinal change in the average position of ice edge of <10 km or a meridional change of <0.1°, which is small compared to some previous estimates [e.g., *Parkinson and Bindschadler*, 1984]. For summer some regional ice extents vary positively with temperature, and others vary negatively.